JC13 Rec'd PCT/PTO 11 DEC 2001

FORM PTO-1390 (REV 10-94) U S DEPARTMENT OF COMMERCE PATENT AND TRADEMARK OFFICE	ATTORNEY'S DOCKET NUMBER 1170/39740 Case 108
TRANSMITTAL LETTER TO THE UNITED STATES DESIGNATED/ELECTED OFFICE (DO/EO/US) CONCERNING A FILING UNDER 35 U.S.C. 371	U S APPLICATION NO (If known, see 37 C F R 1 5) 10/018323

INTERNATIONAL APPLICATION NO.	INTERNATIONAL FILING DATE	PRIORITY DATE CLAIMED
PCT/NZ00/00105	June 21, 2000	June 21, 1999

TITLE OF INVENTION **LINEAR MOTOR**

APPLICANT(S) FOR DO/EO/US **Gerald David Duncan** and **John Henry Boyd**

Applicant herewith submits to the United States Designated/Elected Office (DO/EO/US) the following items and other information

1. ☒ This is a **FIRST** submission of items concerning a filing under 35 U.S.C. 371.
2. ☐ This is a **SECOND** or **SUBSEQUENT** submission of items concerning a filing under 35 U.S.C. 371.
3. ☐ This express request to begin national examination procedures (35 U.S.C. 371(f)) at any time rather than delay examination until the expiration of the applicable time limit set in 35 U.S.C. 371(b) and PCT Articles 22 and 39(l).
4. ☒ A proper Demand for International Preliminary Examination was made by the 19th month from the earliest claimed priority date.
5. ☒ A copy of the International Application as filed (35 U.S.C. 371(c)(2))
   a. ☒ is transmitted herewith (required only if not transmitted by the International Bureau).
   b. ☐ has been transmitted by the International Bureau.
   c. ☐ is not required, as the application was filed in the United States Receiving Office (RO/US).
6. ☐ A translation of the International Application into English (35 U.S.C. 371(c)(2)).
7. ☐ Amendments to the claims of the International Application under PCT Article 19 (35 U S.C. 371(c)(3))
   a. ☐ are transmitted herewith (required only if not transmitted by the International Bureau).
   b. ☐ have been transmitted by the International Bureau.
   c. ☐ have not been made; however, the time limit for making such amendments has NOT expired.
   d. ☐ have not been made and will not be made.
8. ☐ A translation of the amendments to the claims under PCT Article 19 (35 U.S.C. 371(c)(3)).
9. ☒ An oath or declaration of the inventor(s) (35 U.S.C. 371(c)(4)).**(UNEXECUTED)**
10. ☐ A translation of the annexes to the International Preliminary Examination Report under PCT Article 36 (35 U.S.C. 371(c)(5)).

Items 11. to 16. below concern document(s) or information included:

11. ☒ An Information Disclosure Statement under 37 CFR 1.97 and 1.98.
12. ☐ An assignment document for recording. A separate cover sheet in compliance with 37 CFR 3.28 and 3.31 is included.
13. ☐ A FIRST preliminary amendment.
    ☐ A SECOND or SUBSEQUENT preliminary amendment.
14. ☐ A substitute specification.
15. ☐ A change of power of attorney and/or address letter.
16. ☒ Other items or information:
    a. ☒ **International Search Report**
    ☐ **PCT Request**
    ☒ Application Data Sheet

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I hereby certify that this paper or fee is being deposited with the United States Postal Service "Express Mail Post Office Box Addressee" service under 35 CFR 1 10 on the date indicated above and is addressed to the United States Patent and Trademark Office, P O Box 2327, Arlington, VA 22202

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U.S. APPLICATION NO. (If known, see 37 C F R 1 5) 10/018323	INTERNATIONAL APPLICATION NO PCT/NZ00/00105	1170/39740 Case 108

17. ☒ The following fees are submitted:
BASIC NATIONAL FEE (37 CFR 1.492(a)(1)-(5)):

		CALCULATIONS	PTO USE ONLY
Search Report has been prepared by the EPO or JPO	$890.00		
International preliminary examination fee paid to USPTO (37 CFR 1.482)	$750.00		
No international preliminary examination fee paid to USPTO (37 CFR 1.482) but international search fee paid to USPTO (37 CFR 1.445(a)(2))	$770.00		
Neither international preliminary examination fee (37 CFR 1.482) nor international search fee (37 CFR 1.445(a)(2)) paid to USPTO	$1,040.00		
International preliminary examination fee paid to USPTO (37 CFR 1.482) and all claims satisfied provisions of PCT Article 33(2)-(4)	$96.00		
ENTER APPROPRIATE BASIC FEE AMOUNT =		$ 1,040.00	
Surcharge of $130.00 for furnishing the oath or declaration later than months from the earliest claimed priority date (37 CFR 1.492(e)).	☐20 ☐ 30	$	

CLAIMS	NUMBER FILED	NUMBER EXTRA	RATE		
Total claims	38- 20 =	-18-	X $18.00	$ 324.00	
Independent claims	4 - 3 =	-1-	X $84.00	$ 84.00	
MULTIPLE DEPENDENT CLAIM(S) (if applicable)			+ $280.00	$ 280.00	
TOTAL OF ABOVE CALCULATIONS =				$ 1,728.00	
Reduction by ½ for filing by small entity, if applicable. Verified Small Entity Statement must also be filed (Note 37 CFR 1.9, 1.27, 1.28).				$ -0-	
SUBTOTAL =				$ -0-	
Processing fee of $130.00 for furnishing the English translation later than months from the earliest claimed priority date (37 CFR 1.492(f).			☐ 20 ☐ 30 +	$ -0-	
TOTAL NATIONAL FEE =				$ 1,728.00	
Fee for recording the enclosed assignment (37 CFR 1.21(h)). The assignment must be accompanied by an appropriate cover sheet (37 CFR 3.28, 3.31). $40.00 per property			+	$	
TOTAL FEES ENCLOSED =				$ 1,728.00	
				Amount to be refunded:	$
				Amount to be charged:	$

a. ☒ A check in the amount of $ 1,728.00 to cover the above fees is enclosed.

b. ☐ Please charge my Deposit Account No. 20-1495 in the amount of $______ to cover the above fees. A duplicate copy of this sheet is enclosed.

c. ☒ The Commissioner is hereby authorized to charge any additional fees which may be required, or credit any overpayment to Deposit Account No. 20-1495. A duplicate copy of this sheet is enclosed.

NOTE: Where an appropriate time limit under 37 CFR 1.494 or 1.495 has not been met, a petition to revive (37 CFR 1.137(a) or (b)) must be filed and granted to restore the application to pending status.

SEND ALL CORRESPONDENCE TO.

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PTO/PCT Rec'd 11 DEC 2001 10/018323

"LINEAR MOTOR"

Technical Field

This invention relates to a compact linear motor including free piston compressors (also called vibrating and linear compressors) for vapour compression systems and in particular a control system to prevent failure or damage due to unwanted changes of compression level caused by changes to ambient temperature or operating conditions.

Background Art

Compressors, for example refrigerator compressors, are conventionally driven by rotary electric motors. However, even in their most efficient form, there are significant losses associated with the crank system that converts rotary motion to linear reciprocating motion. Alternatively a rotary compressor which does not require a crank can be used but again there are high centripetal loads, leading to significant frictional losses. A Linear compressor driven by a linear motor would not have these losses, and can be designed with a bearing load low enough to allow the use of aerostatic gas bearings as disclosed in US Patent 5,525,845.

Linear reciprocating motors obviate the need for crank mechanisms which characterise compressors powered by rotating electric motors and which produce high side forces requiring oil lubrication. Such a motor is described in US 4,602,174. US Patent 4,602,174 discloses a linear motor design that is extremely efficient in terms of both reciprocating mass and electrical efficiency. This design has been used very successfully in motors and alternators that utilise the Stirling cycle. It has also been used as the motor for linear compressors. However, in the case of compressors designed for household refrigerators the design in US 4,602,174 is somewhat larger and more costly than is desirable for this market.

The piston of a free piston compressor oscillates in conjunction with a spring as a resonant system and there are no inherent limits to the amplitude of oscillation except for collision with a stationary part, typically part of the cylinder head assembly. The piston will take up an average position and amplitude that depend on gas forces and input electrical power. Therefore for any given input electrical power, as either evaporating or condensing

pressure reduces, the amplitude of oscillation increases until collision occurs. It is therefore necessary to limit the power as a function of these pressures.

It is desirable for maximum efficiency to operate free piston refrigeration compressors at the natural frequency of the mechanical system. This frequency is determined by the spring constant and mass of the mechanical system and also by the elasticity coefficient of the gas. In the case of refrigeration, the elasticity coefficient of the gas increases with both evaporating and condensing pressures. Consequently the natural frequency also increases. Therefore for best operation the frequency of the electrical system powering the compressor needs to vary to match the mechanical system frequency as it varies with operating conditions.

Methods of synchronising the electrical voltage applied to the compressor motor windings with the mechanical system frequency are well known. For a permanent magnet motor used in a free piston compressor, a back electromotive force (back EMF) is induced in the motor windings proportional to the piston velocity as shown in Fig 8a. The equivalent circuit of the motor is shown in Fig 8b. An alternating voltage (V) is applied in synchronism with the alternating EMF (αv) in order to power the compressor. US 4,320,448 (Okuda et al.) discloses a method whereby the timing of the applied voltage is determined by detecting the zero crossings of the motor back EMF. The application of voltage to the motor winding is controlled such that the current is zero, at the time at which the EMF intersects with the zero level to allow back EMF zero crossing detection.

Various methods have been used to limit oscillation amplitude including secondary gas spring, piston position detection, piston position calculation based on current and applied voltage (US 5,496,153) measuring ambient and/or evaporating temperature (US 4,179,899, US 4,283,920). Each of these methods requires the cost of additional sensors or has some performance limitation.

DISCLOSURE OF THE INVENTION

It is an object of the present invention to provide a compact linear motor which goes some way to overcoming the abovementioned disadvantages or which will at least provide the public with a useful choice.

Accordingly in a first aspect the present invention may be said to consist in an electric linear motor for driving a reciprocating load comprising:

a stator having a magnetically permeable core with at least one air gap and means for producing a non constant magnetic flux in said stator and said at least one air gap;

an armature having a structure which supports at least one permanent magnet of which at least a substantial portion is located in at least one of said at least one air gap, such that the interaction of the magnetic field of said at least one permanent magnet and said non constant flux in said at least one air gap producing a force on said armature, said armature in use being connected to said load and thereby reciprocating with respect to said stator; and

energisation means for controlling said means for producing an alternating flux such that at least one end of said at least one permanent magnet passes outside the region of substantially uniform flux density present within said at least one of said at least one air gap during a portion of the reciprocal motion of said armature.

In a second aspect the present invention may be said to consist in a refrigerator which uses a compressor characterised in that the compressor and compressor motor are linear devices and said motor comprises:

a stator having a magnetically permeable core with at least one air gap and means for producing a non constant magnetic flux in said stator and said at least one air gap;

an armature having a structure which supports at least one permanent magnet of which at least a substantial portion is located in at least one of said at least one air gap, such that the interaction of the magnetic field of said at least one permanent magnet and said non constant flux in said at least one air gap producing a force on said armature, said armature in use being connected to said load and thereby reciprocating with respect to said stator; and

energisation means for controlling said means for producing an alternating flux such that at least one end of said at least one permanent magnet passes outside the region of substantially uniform flux density present within said at least one of said at least one air gap during a portion of the reciprocal motion of said armature.

In a third aspect the present invention may be said to consist in a vapour compressor comprising:

a piston,

a cylinder,

said piston being reciprocable within said cylinder, the vibrating system of piston, spring and the pressure of said vapour having a natural frequency which varies with vapour

pressure,

a linear brushless DC motor drivably coupled to said piston having at least one winding,

a DC power supply,

commutation means for electronically commutating said at least one winding from said DC supply to provide a supply of current to said at least one winding to reciprocate said piston,

resonant driving means which initiate commutation of said at least one winding to thereby drive said piston at the resonant frequency of said vibrating system,

current controlling means which determine the amount of said supply of current supplied by said commutation means, said determined amount of current being related to said resonant frequency, and which initiate commutation of said at least one winding to thereby limit the amplitude of reciprocation of said piston.

In a forth aspect the present invention may be said to consist in a method for driving and controlling the amplitude of the piston in a free piston vapour compressor wherein said piston reciprocates in a cylinder and wherein the vibrating system of piston, spring and the pressure of said vapour has a resonant frequency which varies with vapour pressure, said method using a linear brushless DC motor having at least one winding and comprising the steps of:

electronically commutating said at least one winding from a DC supply to reciprocate said piston, with commutations timed to drive said piston at the resonant frequency of said vibrating system, limiting the amount of current in said at least one winding by limiting the value of a parameter which determines current supply during commutation to a value which is a function of said resonant frequency.

The "evaporating temperature of the vapour entering the compressor" is also referred to in this specification as the "evaporator temperature". Likewise the "resonant frequency" is also referred to as the "natural frequency".

To those skilled in the art to which the invention relates, many changes in construction and widely differing embodiments and applications of the invention will suggest themselves without departing from the scope of the invention as defined in the appended claims. The disclosures and the descriptions herein are purely illustrative and are not intended to be in

any sense limiting.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a cross-section of a linear compressor according to the present invention;

Figure 2 is a cross-section of the double coil linear motor of the present invention in isolation;

Figure 3 is a cross-section of a single coil linear motor;

Figure 4 is a comparison between a single window prior art linear motor and a short stator linear motor according to the present invention;

Figure 5 is an illustration of the flux lines due to the coil current in a single coil linear motor of the present invention;

Figure 6 is a graph of the motor constant versus magnet position for the preferred embodiment of the present invention;

Figure 7 is a cross-section of a single coil linear motor with partially angled pole faces;

Figure 8a shows motor piston displacement and back EMF waveforms for a free piston compressor motor;

Figure 8b shows an equivalent circuit for such a motor;

Figure 9 shows an inverter for electronically commutating a single phase free piston motor;

Figure 10 shows graphs of maximum motor current as a function of frequency and evaporation temperature for a motor of the present invention;

Figure 11 is a block diagram of the motor control circuit;

Figure 12 is a graph of RMS motor current versus motor winding current decay time;

Figure 13 is a flow chart of the motor control timing program;

Figure 14 is a flow chart of commutation time determination using evaporator temperature and stroke time data; and

Figure 15 shows motor piston displacement and motor current waveforms.

MODE(S) FOR CARRYING OUT THE INVENTION

The present invention provides a method for controlling a linear motor with a number of improvements over the prior art. Firstly it has a reduced size compared to the conventional linear motor of the type described in US4602174 and thus reduces the cost.

This change keeps the efficiency high at low to medium power output at the expense of slightly reduced efficiency at high power output. This is an acceptable compromise for a compressor in a household refrigerator which runs at low to medium power output most of the time and at high power output less than 20% of the time (this occurs during periods of frequent loading and unloading of the refrigerator contents or on very hot days). Secondly it uses a control strategy which allows optimally efficient operation, while negating the need for external sensors, which also reduces size and cost.

While in the following description the present invention is described in relation to a cylindrical linear motor it will be appreciated that this method is equally applicable to linear motors in general and in particular also to flat linear motors. One skilled in the art will require no special effort to apply the control strategy herein described to any form of linear motor. It will also be appreciated that the present invention will be applicable in any form of compressor. While it is described in relation to a free piston compressor it could equally be used in a diaphragm compressor.

A practical embodiment of the invention, shown in Figure 1, involves a permanent magnet linear motor connected to a reciprocating free piston compressor. The cylinder 9 is supported by a cylinder spring 14 within the compressor shell 30. The piston 11 is supported radially by the bearing formed by the cylinder bore plus its spring 13 via the spring mount 25.

The reciprocating movement of piston 11 within cylinder 9 draws gas in through a suction tube 12 through a suction port 26 through a suction muffler 20 and through a suction valve port 24 in a valve plate 21 into a compression space 28. The compressed gas then leaves through a discharge valve port 23, is silenced in a discharge muffler 19, and exits through a discharge tube 18.

The compressor motor comprises a two part stator 5,6 and an armature 22. The force which generates the reciprocating movement of the piston 11 comes from the interaction of two annular radially magnetised permanent magnets 3,4 in the armature 22 (attached to the piston 11 by a flange 7), and the magnetic field in an air gap 33 (induced by the stator 6 and coils 1,2).

A two coil embodiment of present invention, shown in Figure 1 and in isolation in Figure 2, has a current flowing in coil 1, which creates a flux that flows axially along the

inside of the stator 6, radially outward through the end stator tooth 32, across the air gap 33, then enters the back iron 5. Then it flows axially for a short distance 27 before flowing radially inwards across the air gap 33 and back into the centre tooth 34 of the stator 6. The second coil 2 creates a flux which flows radially in through the centre tooth 34 across the air gap axially for a short distance 29, and outwards through the air gap 33 into the end tooth 35. The flux crossing the air gap 33 from tooth 32 induces an axial force on the radially magnetised magnets 3,4 provided that the magnetisation of the magnet 3 is of the opposite polarity to the other magnet 4. It will be appreciated that instead of the back iron 5 it would be equally possible to have another set of coils on the opposite sides of the magnets.

An oscillating current in coils 1 and 2, not necessarily sinusoidal, creates an oscillating force on the magnets 3,4 that will give the magnets and stator substantial relative movement provided the oscillation frequency is close to the natural frequency of the mechanical system. This natural frequency is determined by the stiffness of the springs 13, 14 and mass of the cylinder 9 and stator 6. The oscillating force on the magnets 3,4 creates a reaction force on the stator parts. Thus the stator 6 must be rigidly attached to the cylinder 9 by adhesive, shrink fit or clamp etc. The back iron is clamped or bonded to the stator mount 17. The stator mount 17 is rigidly connected to the cylinder 9.

In a single coil embodiment of the present invention, shown in Figure 3, current in coil 109, creates a flux that flows axially along the inside of the inside stator 110, radially outward through one tooth 111, across the magnet gap 112, then enters the back iron 115. Then it flows axially for a short distance before flowing radially inwards across the magnet gap 112 and back into the outer tooth 116. In this motor the entire magnet 122 has the same polarity in its radial magnetisation.

In the preferred embodiment of the present invention the length of the armature (tooth) faces only extends to, for example, 67% of the maximum stroke (where the edge of the magnet extends to at maximum power output) of the magnet. This is seen in Figure 4 where a conventional prior art linear motor is visually compared against the present invention variable constant design of equivalent power output, both at maximum stroke. It can be seen that the outer edge 200 of the stator tooth does not extend as far as the outer end of the magnet 201. Similarly the inner edge 203 of the other stator tooth does not extend to the inner end of the magnet 204. In contrast in the prior art design the edge of the magnet 205

does match up with the edges of the stator teeth 206,207 at maximum stroke.

At strokes less than, for example, 60% in the present invention the magnet 70 will be in an area of uniform flux density as indicated by the region "a" to "b" in Figure 5, which roughly corresponds where the stator teeth 71 extend to. As the stroke increases past 60% the flux density encountered by the magnet edge 70 reduces as it enters the fringe portion (non-uniform flux density) of the air gap magnetic field - the area outside "b" in Figure 5.

In a further embodiment shown in Figure 7, a stator for a linear motor is shown with angled pole face 503. In its centre the pole face 503 has a flat section 500, which results in the air gap facing that section having substantially uniform flux density. The end of the pole face 503, is angled to give a more progressive transition from the uniform flux density of the centre 500, to the fringe portion 502 (non-uniform flux density) at the end of the pole face 503. Similar to the proceeding embodiments the armature magnet 504, would be driven outside the area of uniform flux density 500, and into the fringe portion 502 of non-uniform flux density.

The "Motor Constant" is defined as the force (in Newtons) generated on the magnet by one Ampere in the motor windings. The motor constant curve, shown in Figure 6 shows how the Motor Constant 300 for the present invention varies with magnet position. Equally the "Motor Constant" can be defined as the back EMF (in Volts) generated when the magnet is moving at one metre/second. When the magnet is in the fringe field (outside "b" in Figure 5), because of the reduced magnetic coupling, more current will be required to generate a given force when compared to that in the uniform flux region (from "a" to "b" in Figure 5). This results in the "variable" motor constant curve 300 associated with the present invention short stator linear motor as shown in Figure 6. This contrasts with the "constant" motor constant curve 301, also seen in Figure 6, inherent in the conventional prior art linear motors.

With the motor constant curve 300 shown in Figure 6 at low and medium strokes (corresponding to strokes of -3mm to +3mm) it will be apparent the present invention has a high motor constant relative to an equivalent convention motor 301, (with less turns and a greater volume of core material). A higher motor constant corresponds to more efficient operation (due to lower invertor losses), therefore at lower power output the present invention is more efficient than an equivalent conventional prior art linear motor. It also

reduces the required cross sectional area of the core.

At high strokes the motor constant is low at the times when the current is increasing most rapidly. This makes it possible to get more current into the motor and thus extract more power from the motor at maximum strokes as compared to an equivalent conventional prior art linear motor. Also such a design with a variable constant that is lowest at maximum stroke tends to make motors driven by square wave voltages more efficient.

Control Strategy

Experiments have established that a free piston compressor is most efficient when driven at the natural frequency of the compressor piston-spring system. However as well as any deliberately provided metal spring, there is an inherent gases spring, the effective spring constant of which, in the case of a refrigeration compressor, varies as either evaporator or condenser pressure varies. The electronically commutated permanent magnet motor already described, is controlled using techniques including those derived from the applicant's experience in electronically commutated permanent magnet motors as disclosed in US 4857814 and WO 98/35428 for example, the contents of which are incorporated herein by reference. Those references disclose the control of a 3 phase rotating motor, but the same control principles can be applied to linear motors. A suitable linear motor need only be a single phase device and a suitable inverter bridge circuit for powering a motor can be of the simple form shown in Figure 9.

By monitoring back EMF zero crossings in the motor winding current commutation can be determined to follow the natural frequency of the piston. Since there is only a single winding, the current flowing through either upper or lower inverter switching devices 411 or 412 must be interrupted so that back EMF can be measured. Controlling the current through the motor winding in accordance with detected back EMF ensures current and back EMF are maintained in phase for maximum system efficiency.

The frequency of operation of the motor is effectively continuously monitored as frequency is twice the reciprocal of the time between back EMF zero crossings. Furthermore according to WO 98/35428 the current decay time through free wheel diodes 413 and 414 after commutation has ceased is directly proportional to the motor current and thus a measure of motor current is available.

The maximum motor current that can be employed before the piston collides with the

cylinder head of the compressor varies depending upon the evaporator temperature and the natural frequency of the vibrating system

Figure 10 shows graphs of maximum permitted motor current against natural mechanical system frequency and condenser temperatures for different evaporating temperatures. These show the dependence of maximum motor current on both these variables. They also demonstrate that condenser temperatures are proportional to mechanical system frequency and thus maximum current control can be achieved without the need for measurement of the third variable, condenser temperature.

The motor control circuit according to this invention is shown in Figure 11. It utilises the observation that mechanical system frequency is related to condenser temperature. In this invention the back EMF signal induced in the motor windings 1 is sensed and digitised by circuit 402 and applied to the input of a microcomputer 403 which computes the appropriate timing for the commutation of current to the motor windings to ensure that the current is in phase with the back EMF. These commutation timing signals switch an inverter 404 (as shown in Figure 11) which delivers current to the motor windings 401. The microcomputer 403 also measures the time between back EMF zero crossings and thereby the period of the EMF waveform. The natural oscillation frequency of the mechanical system is the inverse of the period of the EMF waveform. The microcomputer 403 therefore has a measure of this frequency at all times.

The conventional temperature sensor 405 for measuring the evaporator temperature for defrost purposes is utilised and its output is digitised and supplied as a further input to microcomputer 403.

According to the present invention one method of limiting maximum motor current and thus maximum displacement of the piston is for the microcomputer 403 to calculate a maximum current amplitude for each half cycle of piston oscillation and limit the actual current amplitude to less than the maximum. WO 98/35428 discloses a method of measuring motor current in an electronically commutated permanent magnet motor by utilising the digitised back EMF signal in an unpowered winding to measure the time taken for the current in the motor winding to decay to zero. Use of this technique in the present invention enables microcomputer 403 to limit maximum power without the need for dedicated current sensing or limiting circuitry. The RMS motor current is directly proportional to the time duration of

current decay through the "freewheeling" diodes 413 or 414 after the associated inverter switching device has switched off. The current decay results of course from the motor winding being an inductor which has stored energy during commutation and which must be dissipated after commutation has ceased. A graph of RMS motor current against current decay duration (which is a simplification of Figure 6 in WO 98/35428) is shown in Figure 12.

Another preferred method is to limit the time that the current is commutated on instead of limiting the maximum current value. Figure 15 shows the current waveform under such control. This is in effect pulse width modulation (PWM) with only one modulated current pulse per commutation interval. With this method a delay time from the back EMF zero crossing is computed to minimise the phase angle between the Motor Current and the back EMF for maximum efficiency. The invertor switch supplying current is turned off at a time in the motor half cycle to allow, after a current decay period, time to monitor zero crossing of the back EMF to determine the start commutation for the next half cycle. The commutation time is also compared with a maximum commutation time appropriate to the motor frequency and evaporator temperature to ensure maximum amplitude of the piston stroke is not exceeded.

A flow diagram of the microcomputer control strategy to implement this method is shown in Figures 13 and 14. Referring to Figure 13 when the compressor is first powered (421), or is powered after sufficient time delay to ensure pressures are equalised in the refrigeration system, the compressor runs at a minimum frequency. The stroke period of this minimum frequency is measured as Run_Stroke and shown in the microcomputer as Low_Stroke and a minimum Commutation Time is set for this value (428). For each subsequent stroke the stroke period is measured and defined as the parameter Run_Stroke (424). The difference between Run_Stroke and Low_Stroke is computed (431, Figure 14). This difference is called Period_Index. The Period_Index is used in this sub-routine as an index pointer in a lookup table of maximum commutation times for different stroke times (frequencies). This table is called the Pulse_Limit_Value Table. In this instance there are 7 lookup tables (433 to 439) corresponding to 7 ranges of Evaporating Temperature (440 to 465).

The motor control circuit is typically included in a Temperature Control loop in the

conventional manner in order to maintain the temperature of the enclosed refrigerated space of the refrigeration system. This control loop will be setting desired values for the power to be applied to the motor windings depending on the operating conditions of the refrigeration system. These values of desired power will correspond to values of commutation time. These values of Commutation Time are compared on a stroke by stroke basis with the Pulse_Limit_Value (440, Figure 14). If the Desired value of commutation time is greater than the Pulse_Limit_Value then the commutation time is limited to the Pulse_Limit_Value. This value sets the Commutation Timer (425) which controls the ON period of the relevant inverter switching device. As previously explained, Motor current can also be used in a similar manner to limit power applied to the motor to safe levels, but even where commutation time is being controlled it is desirable to measure motor current in the manner previously described and compare it with a stored absolute maximum value (426) which if exceeded will cause the microcomputer program to reset (427).

Of course other methods of determining maximum commutation time and/or maximum current value are feasible, for instance if the microcomputer is sufficiently powerful, for example recent advances in DSP chip technology, these values can be computed directly without the need for lookup tables.

If the DC power supply Voltage supplied to the inverter bridge of Figure 9 varies significantly this will result in variation of Motor Current for any given commutation time which should be allowed for. It may be desirable for maximum accuracy for the microprocessor to sense this and compensate accordingly.

It will be appreciated that use of the present invention in a refrigerator reduces the profile, size and weight of the motor compared to that of conventional designs. Also because the mass of the moving parts is lower than that of a conventional refrigerator compressor:

- the level of vibration is reduced,
- the noise level is reduced,
- the working stresses on the moving parts are reduced.

CLAIMS:

1. An electric linear motor for driving a reciprocating load comprising:

a stator having a magnetically permeable core with at least one air gap and means for producing a non constant magnetic flux in said stator and said at least one air gap;

an armature having a structure which supports at least one permanent magnet of which at least a substantial portion is located in at least one of said at least one air gap, such that the interaction of the magnetic field of said at least one permanent magnet and said non constant flux in said at least one air gap producing a force on said armature, said armature in use being connected to said load and thereby reciprocating with respect to said stator; and

energisation means for controlling said means for producing an alternating flux such that at least one end of said at least one permanent magnet passes outside the region of substantially uniform flux density present within said at least one of said at least one air gap during a portion of the reciprocal motion of said armature.

2. An electric linear motor as claimed in claim 1 wherein said means for producing an alternating magnetic flux comprises at least one coil wound around a portion of said stator and energised with a non constant voltage.

3. An electric linear motor as claimed in claim 2 wherein said energisation means comprises a commutation circuit including a direct current power supply, switching devices connected to said power supply to supply current to said at least one coil and a programmed digital processor including memory and input-output ports, at least one of said ports being connected to said commutation circuit to supply switching control signals thereto.

4. An electric linear motor as claimed in claim 1 wherein the displacement of said at least one permanent magnet at which said at least one end of said at least one magnet passes outside said region of substantially uniform flux density is 67% of the maximum displacement.

5. A refrigerator which uses a compressor characterised in that the compressor and

compressor motor are linear devices and said motor comprises:

a stator having a magnetically permeable core with at least one air gap and means for producing a non constant magnetic flux in said stator and said at least one air gap;

an armature having a structure which supports at least one permanent magnet of which at least a substantial portion is located in at least one of said at least one air gap, such that the interaction of the magnetic field of said at least one permanent magnet and said non constant flux in said at least one air gap producing a force on said armature, said armature in use being connected to said load and thereby reciprocating with respect to said stator; and

energisation means for controlling said means for producing an alternating flux such that at least one end of said at least one permanent magnet passes outside the region of substantially uniform flux density present within said at least one of said at least one air gap during a portion of the reciprocal motion of said armature.

6. A vapour compressor comprising:

a piston,

a cylinder,

said piston being reciprocable within said cylinder, the vibrating system of piston, spring and the pressure of said vapour having a natural frequency which varies with vapour pressure,

a linear brushless DC motor drivably coupled to said piston having at least one winding,

a DC power supply,

commutation means for electronically commutating said at least one winding from said DC supply to provide a supply of current to said at least one winding to reciprocate said piston,

resonant driving means which initiate commutation of said at least one winding to thereby drive said piston at the resonant frequency of said vibrating system,

current controlling means which determine the amount of said supply of current supplied by said commutation means, said determined amount of current being related to said resonant frequency, and which initiate commutation of said at least one winding to thereby limit the amplitude of reciprocation of said piston.

7. A vapour compressor as claimed in claim 6 further comprising:

a sensor for measuring a property of the vapour entering the compressor which is an indicator of the pressure,

and wherein said determined amount of current also being related to said measured indicative property.

8. A vapour compressor as claimed in claim 7 wherein said sensor measures a property of the vapour entering the compressor which is an indicator of the pressure on evaporation.

9. A vapour compressor as claimed in any one of claims 6 to 8 wherein said resonant driving means comprising:

back EMF detection means for sampling the back EMF induced in said at least one winding when commutation current is not flowing and for detecting back EMF zero-crossings and producing timing signals derived therefrom, and

resonant commutation means which initiate commutation of said at least one winding in response to said zero crossing timing signals to thereby drive said piston at the resonant frequency of said vibrating system.

10. A vapour compressor as claimed in claim 9 further comprising

current detection means for measuring the current flowing in said at least one winding during commutation,

wherein said current controlling means terminates commutation when said measured current reaches said determinated amount of current.

11. A vapour compressor as claimed in claim 10 wherein said commutation means includes switching devices connected to said DC power supply to supply current to said at least one winding and unidirectional current devices which supply a current path to dissipate energy stored in each winding after supply of current through a switching device has terminated, and said current detection means comprises:

a programmed digital processor including memory and input-output ports, a first port being connected to the output of said back EMF detection means and a second group of ports

being connected to said commutation means to supply switching control signals thereto,

software stored in said memory to cause said processor to determine a measure of motor current based on intervals between those zero crossings of said back EMF, which represent the duration of a current pulse produced in said at least one winding due to dissipation of stored energy by said unidirectional current devices after supply of current has been removed from said at least one winding.

12. A vapour compressor as claimed in any one of claims 6 to 11 wherein said current controlling means further comprises:

means for measuring said resonant frequency,

a memory which stores at least one look up table containing maximum current commutation values for each of a plurality of resonant frequencies for said vibrating system, and

value selection means for selecting the value in said table which corresponds to said measured resonant frequency and for supplying same to said commutation controlling means.

13. A vapour compressor as claimed in either claims 7 or 8 wherein said current controlling means further comprising:

means for measuring said resonant frequency,

a memory which stores a plurality of look up tables stored in said memory containing maximum current commutation values for each of a plurality of resonant frequencies for said vibrating system, each look up table corresponding to a non-overlapping range of said indicative property, and

table selection means for selecting a look up table to use on the basis of the measured value of said indicative property,

value selection means for selecting the value in said table which corresponds to said measured resonant frequency and for supplying same to said commutation controlling means.

14. A vapour compressor as claimed in any one of claims 6 to 11 wherein said current controlling means includes a processor storing instructions which when executed calculate said determined amount of current based on a mathematically expressible relationship to at

least said measured resonant frequency and optionally said measured indicative property.

15. A method for driving and controlling the amplitude of the piston in a free piston vapour compressor wherein said piston reciprocates in a cylinder and wherein the vibrating system of piston, spring and the pressure of said vapour has a resonant frequency which varies with vapour pressure, said method using a linear brushless DC motor having at least one winding and comprising the steps of:

electronically commutating said at least one winding from a DC supply to reciprocate said piston, with commutations timed to drive said piston at the resonant frequency of said vibrating system, limiting the amount of current in said at least one winding by limiting the value of a parameter which determines current supply during commutation to a value which is a function of said resonant frequency.

16. A method as claimed in claim 15 further comprising the step of measuring a property of the vapour entering the compressor which is an indicator of the pressure, wherein said selected maximum current commutation value is also a function of said measured indicative property.

17. A method as claimed in claim 16 wherein said measured indicative property is an indicator of the pressure on evaporation.

18. A method as claimed in any one of claims 15 to 17 wherein said step of driving said piston at the resonant frequency of said vibrating system comprises the steps of:

unpowering said at least one winding at various intervals and detecting zero-crossings of the back EMF induced in said at least one winding, using the zero-crossing timing information to initiate commutation of said at least one winding to thereby drive said piston at the resonant frequency of said vibrating system.

19. A method as claimed in claim 18 wherein said step of electronic commutation comprises using commutation means includes switching devices connected to said DC power supply to supply current to said at least one winding and unidirectional current devices which

supply a current path to dissipate energy stored in each winding after supply of current through a switching device has terminated, measuring motor current based on intervals between those zero crossings of said back EMF, which represent the duration of a current pulse produced in said at least one winding due to dissipation of stored energy by said unidirectional current devices after supply of current has been removed from said at least one winding, and terminating commutation when said measured current reaches said determinated amount of current.

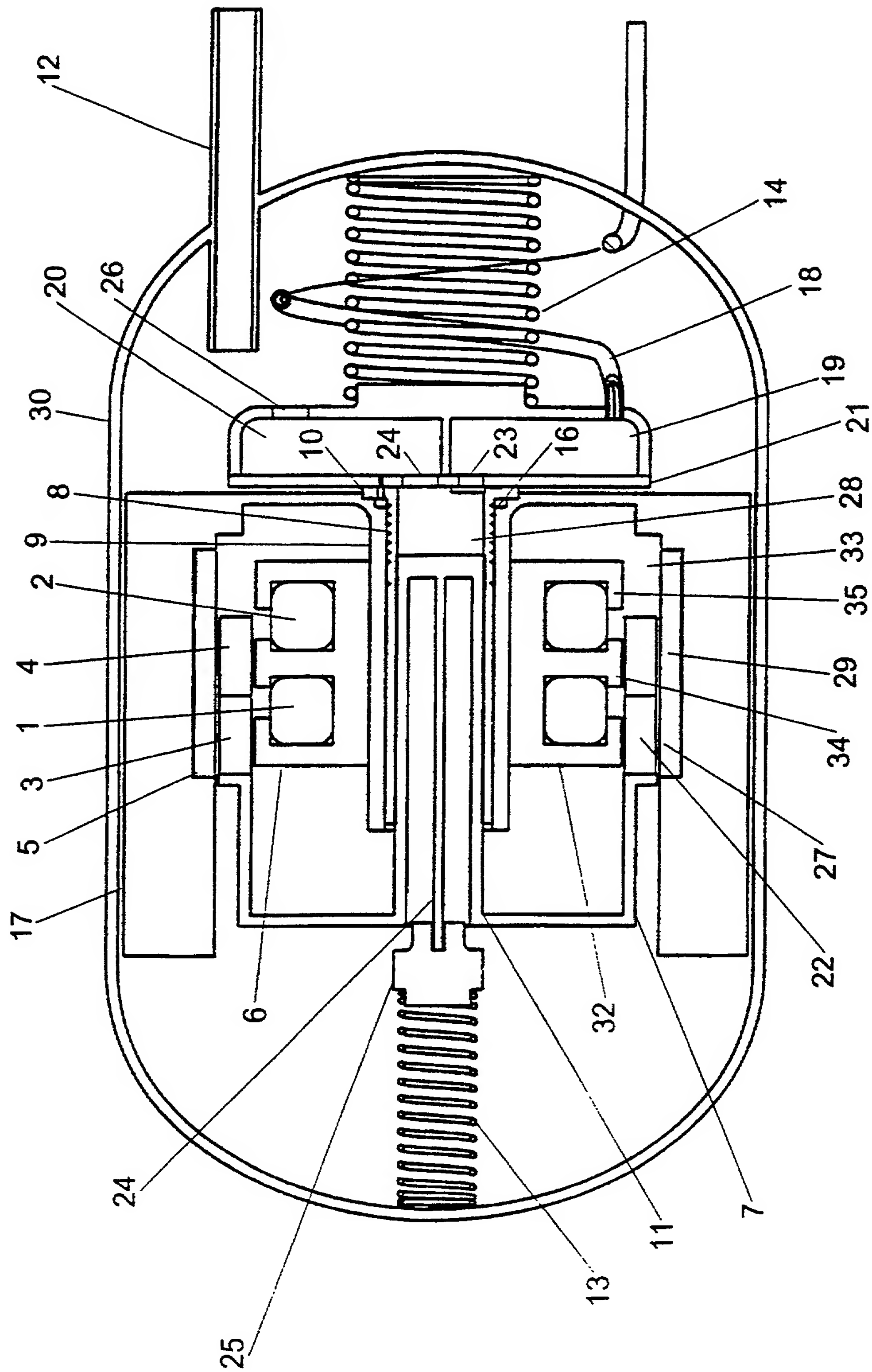
20. A method as claimed in either claims 16 or 17 further comprising a step of measuring a property of the vapour entering the compressor which is an indicator of the pressure on evaporation, wherein said maximum current commutation value is selected from one of a set of look up tables containing maximum current commutation values for each of a plurality of resonant frequencies for said vibrating system and selecting the value which corresponds to the measured resonant frequency, each look up table corresponding to a non-overlapping range of said indicative property and being selected on the basis of the measured value of said indicative property.

21. A method according to claim 20 wherein said parameter which is limited is the magnitude of the current and said look up tables store maximum current values.

22. A method according to claim 20 wherein parameter which is limited is the duration of commutation and said look up tables store maximum commutation duration values.

23. A vapour compressor according to claim 6 wherein instead of said piston and said cylinder said compressor is a diaphragm type compressor.

24. A method according to claim 15 wherein instead of said piston and said cylinder said compressor is a diaphragm type compressor.


12
14
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28
9
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1
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11
7

FIG. 1

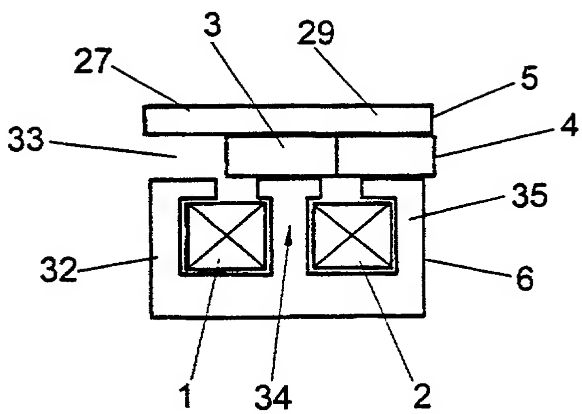


FIG. 2

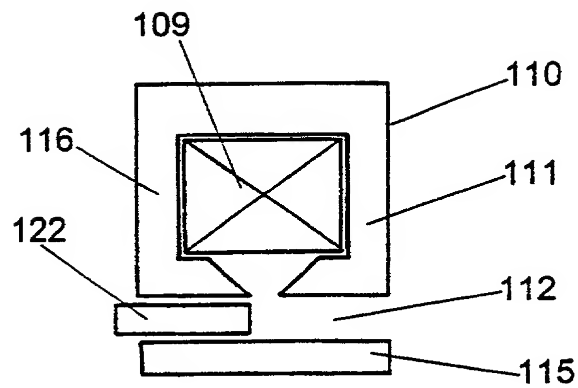


FIG. 3

FIG. 4

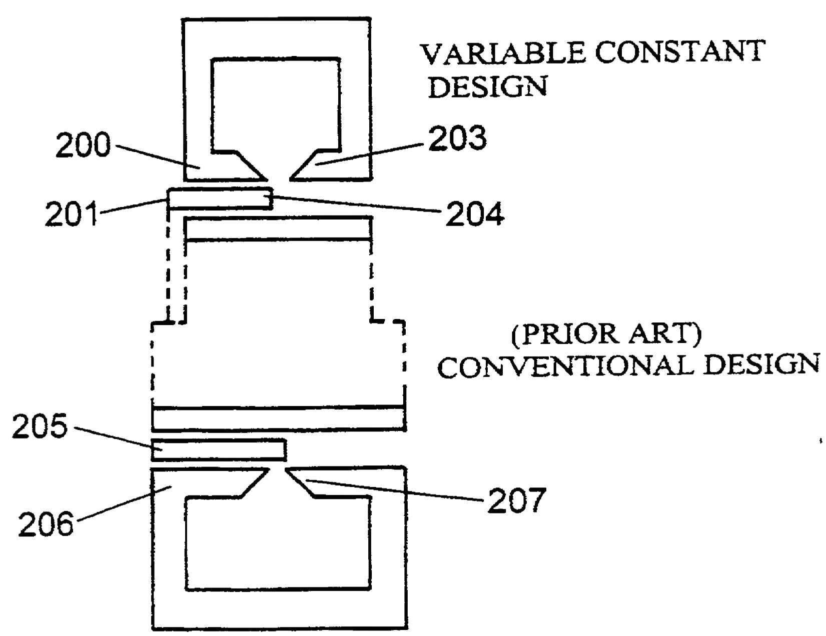


FIG. 5

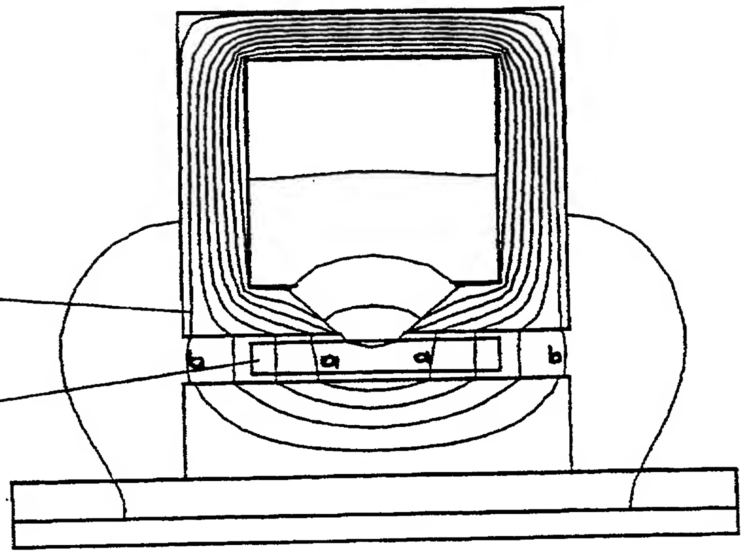
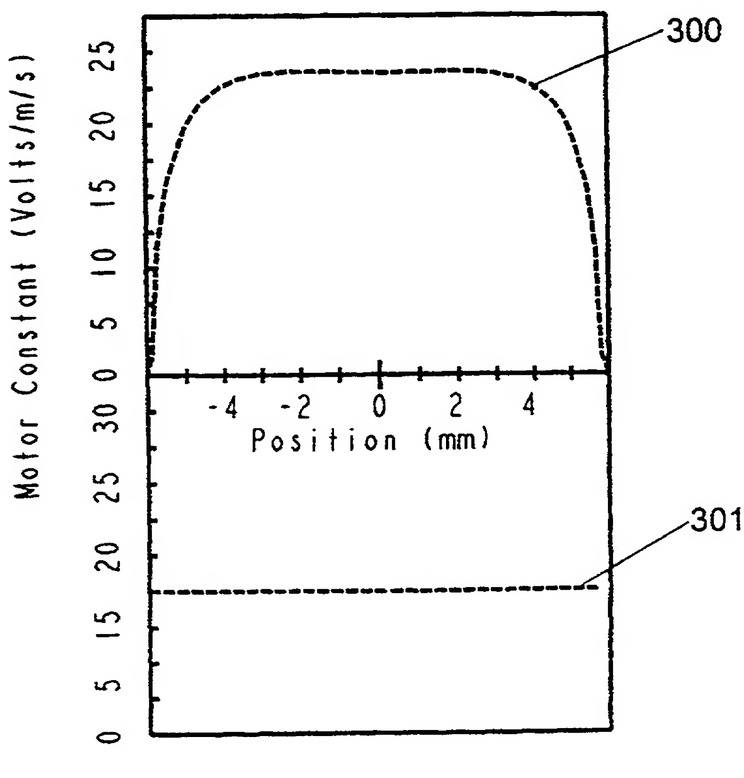

71
70
b
a
a
b

FIG. 6


Motor Constant (Volts/m/s)
Position (mm)
300
301
0
5
10
15
20
25
30
-4
-2
0
2
4

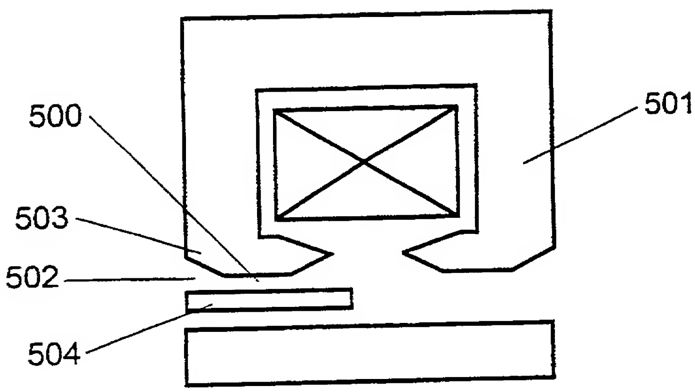


FIGURE 7

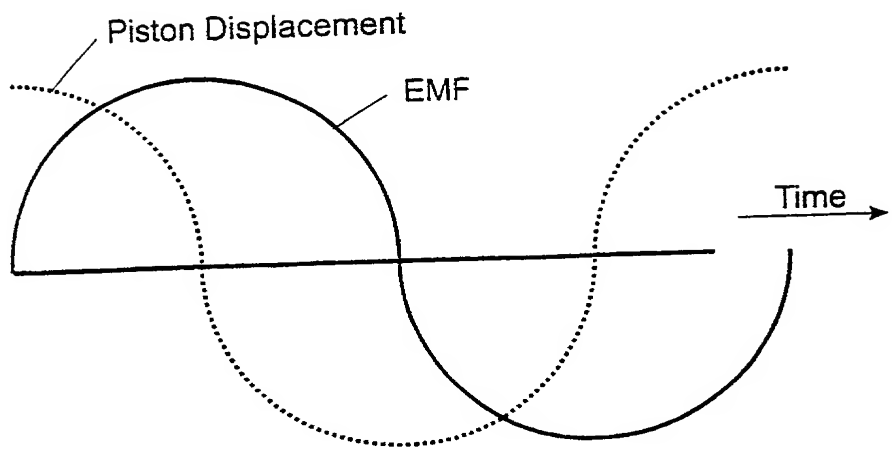


FIGURE 8a
Motor EMF and Displacement Waveforms

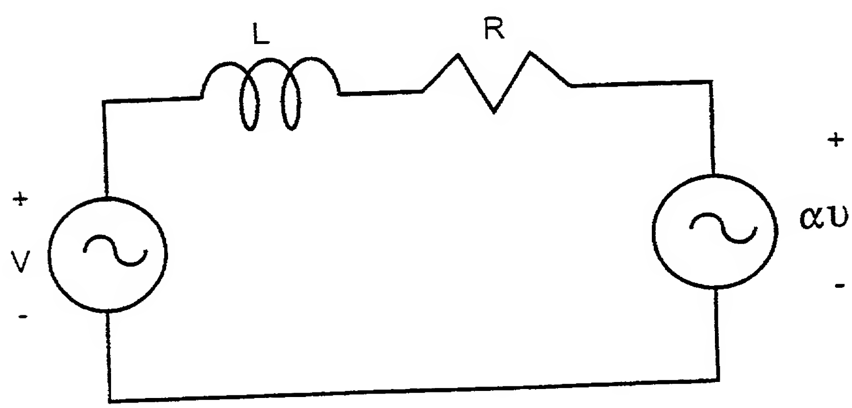


FIGURE 8b
Motor Equivalent Circuit

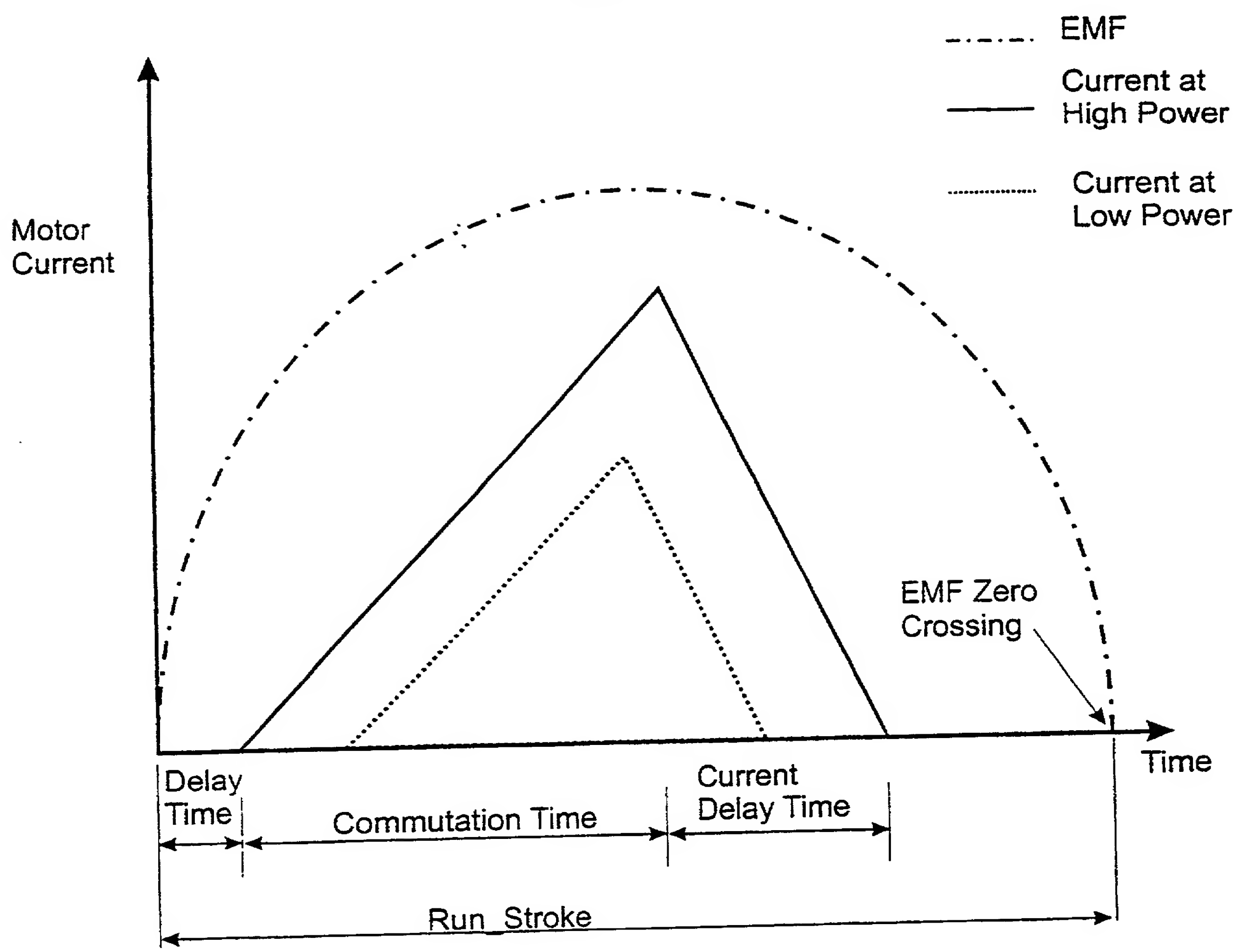


FIGURE 15

Motor Current Waveform and Timing

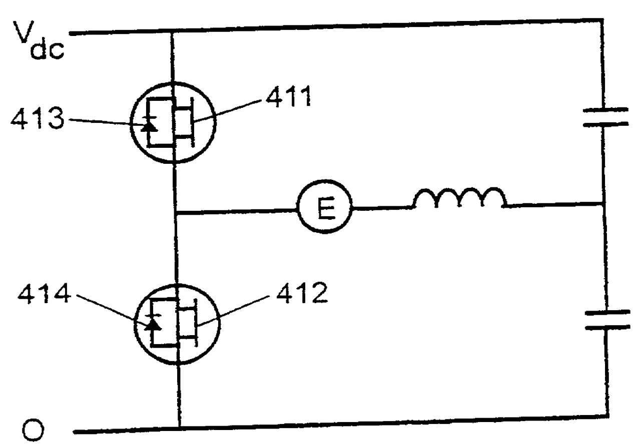


FIGURE 9

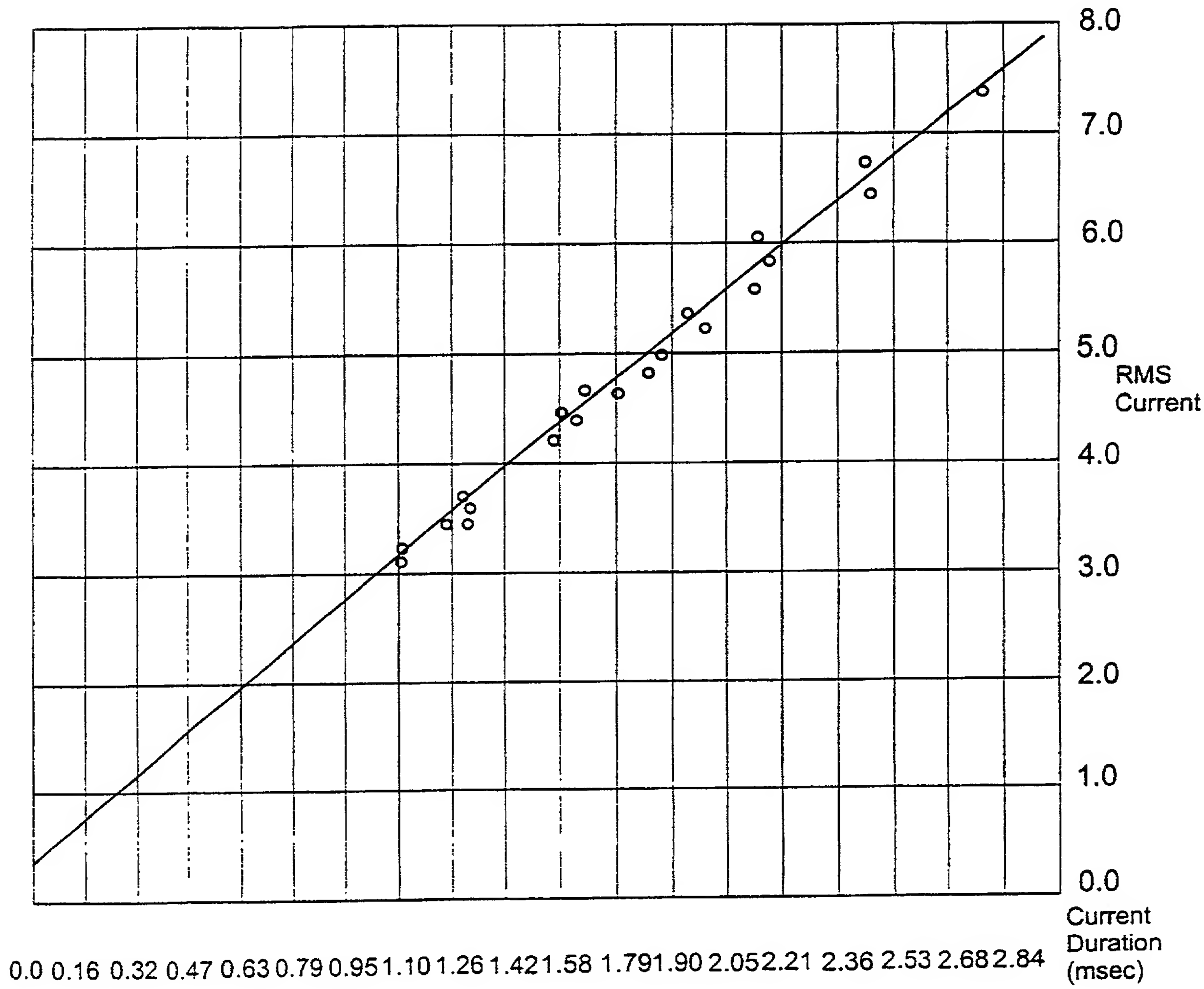

8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
RMS
Current
0.0 0.16 0.32 0.47 0.63 0.79 0.95 1.10 1.26 1.42 1.58 1.79 1.90 2.05 2.21 2.36 2.53 2.68 2.84
Current
Duration
(msec)

FIGURE 12

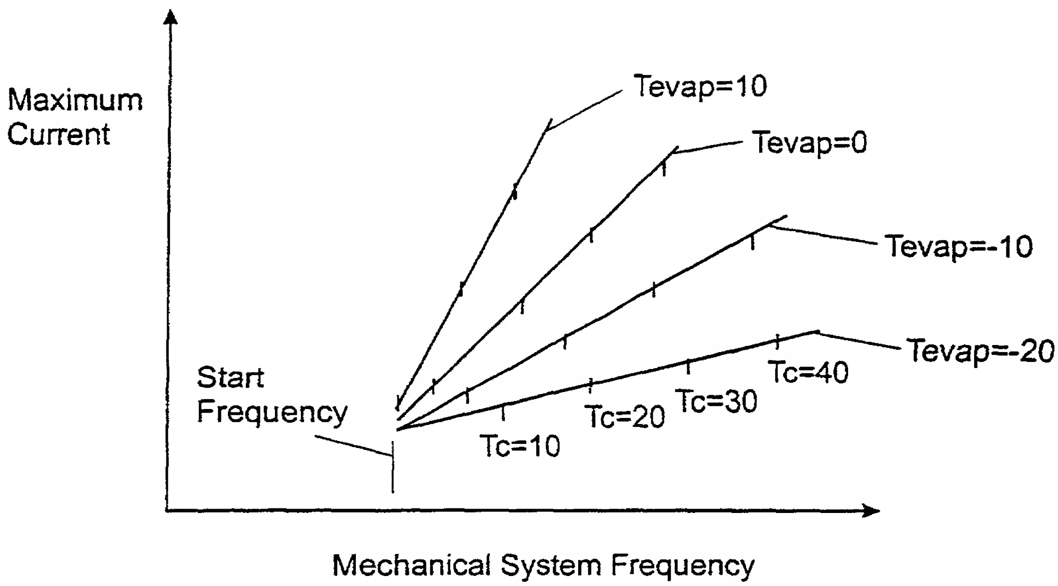


FIGURE 10

Maximum Current as a function of Evaporation Temperature and Frequency

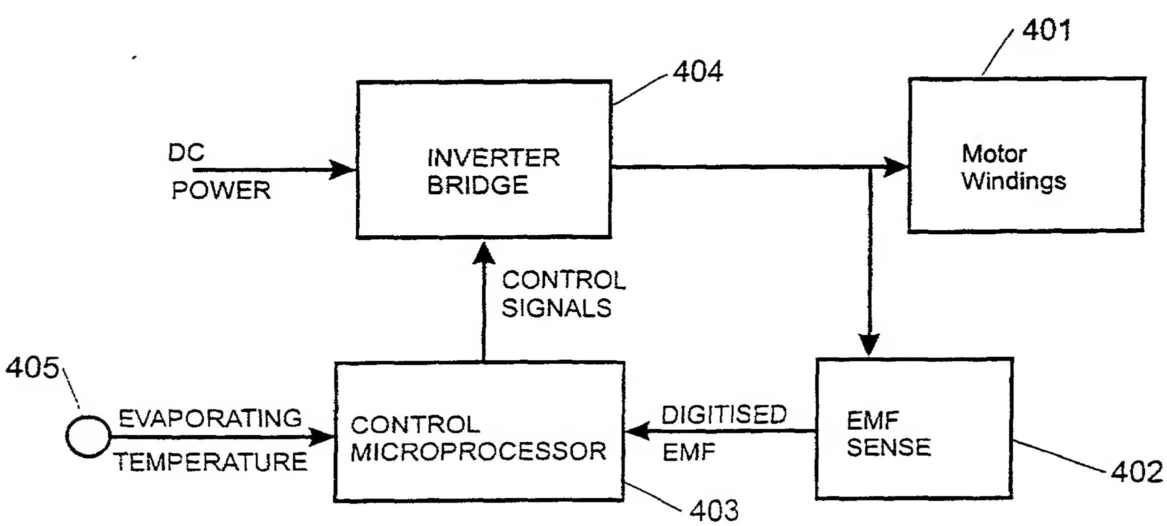


FIGURE 11

Block diagram of the motor control circuit

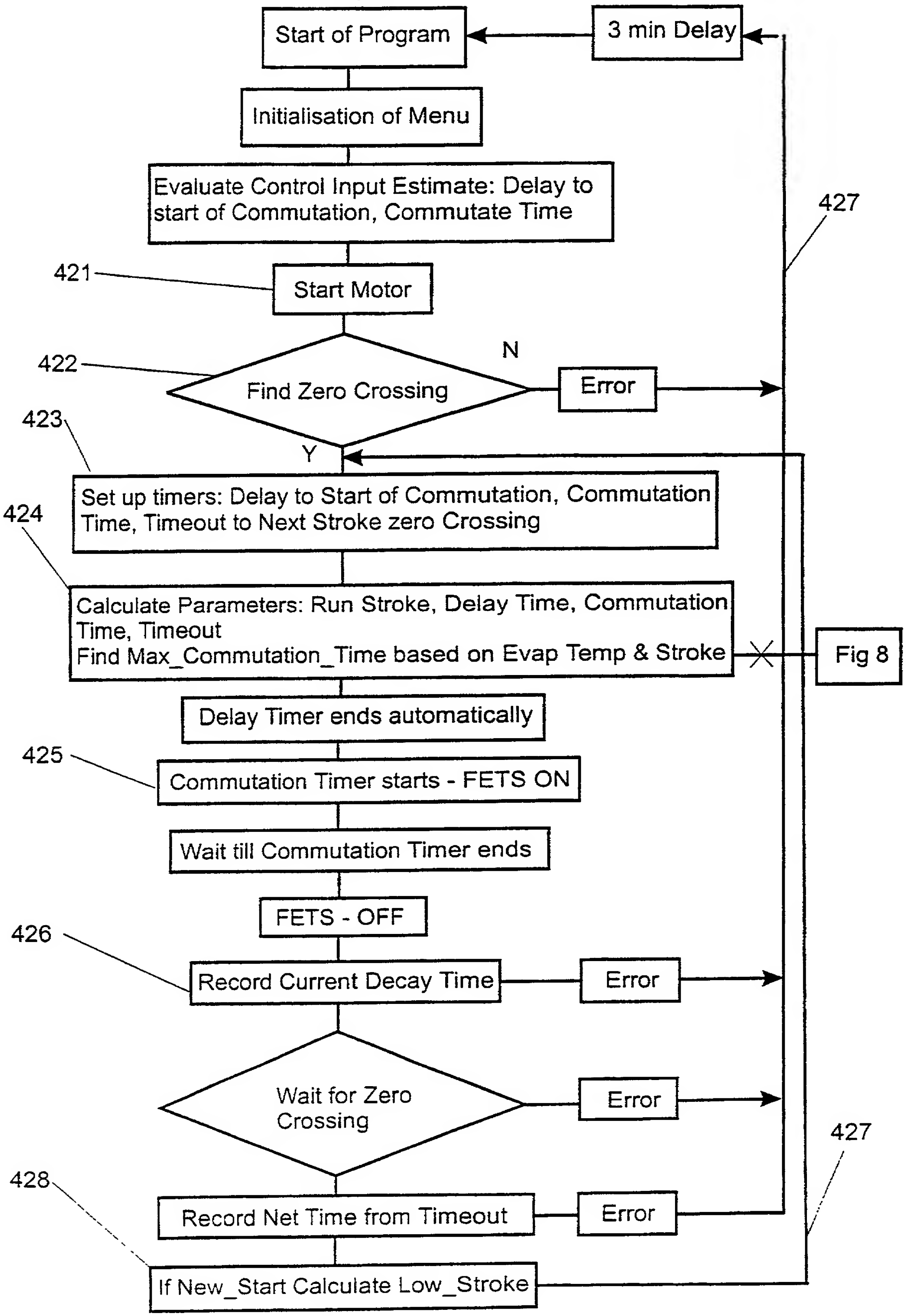


FIGURE 13

Control Microcomputer Motor Control Timing Flow Chart

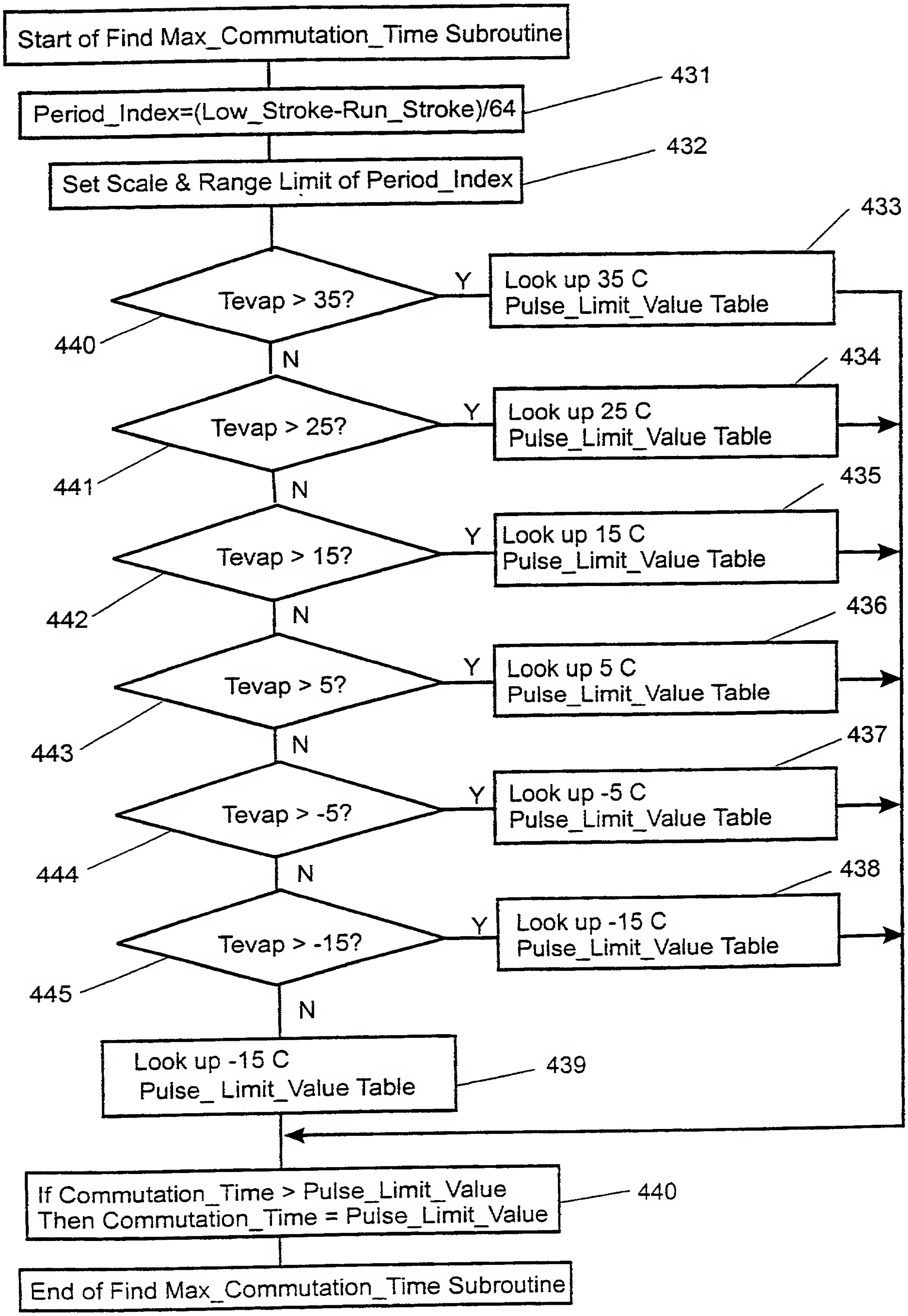


FIGURE 14

Calculation of Commutation Time Limit based on Evap Temp & Stroke Time

DECLARATION AND POWER OF ATTORNEY FOR PATENT APPLICATION

As a below named inventor, I hereby declare that:

My residence, post office address and citizenship are as stated below next to my name,

I believe I am the original, first and sole inventor (if only one name is listed below) or an original, first and joint inventor (if plural names are listed below) of the subject matter which is claimed and for which a patent is sought on the invention entitled: LINEAR MOTOR, the specification of which

(check one) [ ] is attached hereto.
[✓] was filed on December 11, 2001 as
Application Serial No. 10/018,323
and was amended on ________________.
(if applicable)

I hereby state that I have reviewed and understand the contents of the above identified specification, including the claims, as amended by any amendment referred to above.

I acknowledge the duty to disclose information which is material to patentability as defined in Title 37, Code of Federal Regulations, §1.56.

I hereby claim foreign priority benefits under Title 35, United States Code, §119 of any foreign application(s) for patent or inventor's certificate listed below and have also identified below any foreign application for patent or inventor's certificate having a filing date before that of the application on which priority is claimed:

Prior Foreign Application(s) (Number)	(Country)	(Day/Month/Year Filed)	Priority Claimed Yes	No
PCT/NZ00/00105	New Zealand	21/06/00	[✓]	[ ]
336375	New Zealand	21/06/99	[✓]	[ ]
500519	New Zealand	19/10/99	[✓]	[ ]

I hereby claim the benefit under Title 35, United States Code, §120 of any United States application(s) listed below; insofar as the subject matter of each of the claims of this application is not disclosed in the prior United States application in the manner provided by the first paragraph of Title 35, United States Code, §112, I acknowledge the duty to disclose material information as defined in Title 37, Code of Federal Regulations, §1.56(a) which occurred between the filing date of the prior application and the national or PCT international filing date of this application:

(Application Serial No.)	(Filing Date)	(Status: patented, pending, abandoned)

POWER OF ATTORNEY: As a named inventor, I hereby appoint the following attorney(s) and/or agent(s) to prosecute this application and transact all business in the Patent and Trademark Office connected therewith:

7 Richard A. Giangiorgi, Reg. 24,284; Raiford A. Blackstone, Jr., Reg. 25,156; David J. Marr, Reg. 32,915; Linda L. Palomar, Reg. 37,903; James R. Foley, Reg. 39,979; James A. O'Malley, Reg. 45,952 and Paige A. Kitzinger, Reg. 45,219.

SEND CORRESPONDENCE TO: TREXLER, BUSHNELL, GIANGIORGI, BLACKSTONE & MARR, LTD.
105 W. ADAMS STREET, CHICAGO, IL 60603

DIRECT TELEPHONE CALLS TO: (312) 704-1890 RAIFORD A. BLACKSTONE, JR.

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

Full name of sole or first inventor GERALD DAVID DUNCAN

Inventor's signature ________________ Date April 3, 2002

Residence Auckland, New Zealand NZ
Citizenship New Zealand
Post Office Address 42 Henley Road, Mt Eden, Auckland, New Zealand

(Supply similar information and signature for second and subsequent joint inventors.)

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

Full name of second inventor 2-00 **JOHN HENRY BOYD**

Inventor's signature John H Boyd Jr. Date April 3, 2002

Residence ~~Holland, Missouri~~ MI

Citizenship United States of America

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